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OVERVIEW OF POWERED-LIFT TECHNOLOGY

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SUMMARY

This introductory paper is intended to set the stage for the conference by reviewing progress to date in the powered-lift field. The concept and application of powered lift and the effects of some fundamental design variables are discussed. A brief chronology of significant developments in the field is also presented and the direction of research efforts in recent years is indicated. All powered-lift concepts are included, but emphasis is on the two externally blown schemes which involve blowing either above or below the wing and which are now being utilized in the YC-14 and YC-15 airplanes. This review deals primarily with aerodynamics and vehicle design, and only touches briefly on the areas of acoustics, propulsion, and loads.

INTRODUCTION

It is perhaps appropriate to start this review with a bit of historical background which illustrates one of the factors that spurred interest in powered lift back in the 1950's. Richard E. Kuhn brought out this point very well by the use of figure 1 which is a history of maximum lift development from the Wright Brothers to the present day. The upper solid line shows that with the introduction of trailing-edge flaps and with the continuing refinement and sophistication of these flaps, the maximum lift coefficient $C_{L,max}$ obtained in wind-tunnel tests increased at a rapid rate up until the 1940's but at a much more modest rate afterward. Of course, the values of $C_{L,max}$ attained with operational aircraft lagged well behind the wind-tunnel progress at first, but it later became apparent that airplanes would soon be using up most of the mechanical-flap high-lift technology developed in the wind tunnel. This trend was foreseen by researchers in the early 1950's who recognized that the ceiling on $C_{L,max}$ obtainable with mechanical flaps could be bypassed by making full use of the energy of the turbojet propulsion engines to augment wing lift, as indicated by the dashed line. Exploratory research on the jet-flap principle was therefore started in an effort to realize this potential.

In this jet-flap concept, a high-velocity jet sheet is turned downward by a trailing-edge flap and effectively increases the chord of the flap to produce higher lift. The total lift produced is made up of the three components shown in figure 2: the power-off lift produced by the wing and flap, the lift due to thrust deflection (that is, the vertical component of the thrust), and powered circulation lift which is the additional circulation lift induced on the wing and flap by the presence of the jet sheet. The proportions of the three components can vary quite a bit, depending on the type of flap and the particular powered-lift concept used.

POWERED-LIFT CHRONOLOGY

A number of different concepts have been studied as indicated by the powered-lift chronology presented in figure 3. Dates are shown for the first research conducted on a given concept and for the first flight of an airplane incorporating the concept.

The blowing boundary-layer-control (BLC) scheme illustrated at the top is not usually considered a true powered-lift concept since it only uses engine bleed air and hence does not make full use of the available engine thrust. It is included here, however, because of its basic similarity to the jet flap and because some of the work on blowing BLC provided useful information in the development of the jet flap. Exploratory studies of blowing BLC were carried out as early as the 1920's but it was not until the 1940's and 1950's that systematic research was conducted that lead to application of the concept. Some of the most impressive work was done on the Navy's F9F-5 airplane in the early 1950's under the direction of John Attinello (ref. 1). A number of other aircraft with blowing BLC have been flown, including the Boeing 367-30 airplane which was used by NASA for low-speed flight research in the early 1960's. (See fig. 4.)

The principle of the jet flap was proposed and verified by Schubauer in 1932, but very little attention was given to the concept until 20 years later when Attinello's studies in the United States (ref. 1) and Davidson's studies in England (ref. 2) showed great promise for the jet flap. This work led to extensive research programs on the concept in England, France, and the United States. (For example, see refs. 1 to 4.) The Hunting jet flap research airplane (fig. 5) was built in the early 1960's to study the flight characteristics associated with the jet flap. (See ref. 5.) Unfortunately, the airplane had a number of deficiencies which limited its usefulness as a research aircraft.

In the late 1950's De Havilland of Canada initiated research on a variation of the jet flap called the augmentor wing. This concept incorporates a shroud assembly over the flap to create an ejector system which augments the thrust of the nozzle by entraining additional air. The augmentor wing was the subject of a comprehensive research program carried out jointly by NASA and the Canadian government starting in 1965. This program culminated in the design and construction of the C-8 augmentor wing research airplane by Boeing and De Havilland. (See fig. 6.) The aircraft was first flown in 1972 and since that time has been used in a joint NASA-Ames and Canadian flight research program. (See ref. 6.)

Both the augmentor wing and the jet flap proved to be very efficient aerodynamically in that they produced a large increase in wing lift with a given amount of engine thrust. But they are internally blown systems and hence suffer the disadvantage of requiring internal ducting which adds to the weight, cost, and complexity of the wing structure.

In an effort to eliminate internal ducting and to provide much simpler powered-lift systems, NASA Langley Research Center started work in the 1950's on the so-called "externally blown systems" - the externally blown flap used with conventional pod-mounted engines, and the upper surface blown flap. Exploratory research was first carried out on the externally blown flap in 1956 (ref. 7); research on the upper surface blown flap started about a year later (ref. 8). Initial results appeared to be promising for both concepts. A fairly extensive research program was carried out to develop the technology for the externally blown flap; but there were no indications of serious interest by the industry in applying the concept until Boeing incorporated it in its proposal for the C-5 competition. Although Boeing's entry did not win, this show of interest accelerated the research on the externally blown flap and led to an earlier build-up of the technology base required for application of the concept. The culmination of all this research is, of course, the McDonnell-Douglas YC-15 AMST (fig. 7) which has been flying since August 1975.

As pointed out earlier, the initial results obtained on the concept for the upper surface blown flap in 1957 appeared to be promising. The aerodynamic performance was comparable with that of the externally blown flap, and preliminary noise studies showed it to be a potentially quieter concept because of the shielding effect of the wing. (See ref. 9.) However, since the upper surface blowing arrangement involved a change in engine location away from the generally accepted underslung pods and since there was at that time no special concern with the noise problem, research on the upper surface blown flap was dropped after the initial studies. Research was resumed in the early 70's when it was becoming apparent that the externally blown flap might have difficulty meeting increasingly stringent noise requirements. Since that time, of course, research on the upper surface blown flap has been carried out at an accelerated pace; this research lead to the Boeing YC-14 AMST (fig. 8) which will make its first flight within a few months and to the NASA quiet short haul research aircraft (fig. 9) which should be flying in about 3 years.

As the conference proceeds, you will note that there is special emphasis on the upper surface blown flap, for this is the concept which has been researched most extensively since the last NASA powered-lift conference held in 1972.

PERFORMANCE

Now, let us turn to some general performance considerations for powered-lift aircraft. The landing performance will be considered since it is generally more critical than take-off performance for these aircraft. Some of the factors involved in landing-field length are illustrated in figure 10. On this plot of wing loading against approach speed and the corresponding operational field length, there is a family of curves representing different approach lift coefficients. The band of values for 1.5 to 1.8 is for conventional airplanes with mechanical flaps. Note that these values are approach lift coefficients which are considerably lower than maximum lift coefficients because of the various angle-of-attack and speed margins required for safety of operation. The hatched area represents typical powered-lift conditions in the higher wing loading range and extends from field lengths of about 609.6 m (2000 ft) to about 1371.6 m

(4500 ft). Aircraft which use the shorter field lengths, 609.6 m (2000 ft) to about 1066.8 m (3500 ft), are usually classified as STOL or short take-off and landing aircraft; whereas those using the 1066 8- to 1371.6-m (3500- to 4500-ft) field lengths are termed RTOL, or reduced take-off and landing aircraft. The approach lift coefficients can vary from values as low as 2 for the RTOL to values of 4 or 5 for the STOL. Of course, lower wing loadings can be used rather than higher lift coefficients to obtain the shorter field lengths, but this usage can lead to undesirable reductions in cruise performance and ride qualities.

Now, consider the additional power which must be installed in the airplane to obtain powered lift. Figure 11 shows the airplane thrust-weight ratios required to produce certain values of $C_{L,max}$ and approach lift coefficients for an externally blown concept. As an example of a high-performance STOL case, let us take an approach C_L of 4 which gives a landing field length of about 609.6 m (2000 ft) with a wing loading of 3830 N/m^2 (80 lb/ft^2). The thrust-weight ratio required in this case is about 0.5 or about twice the installed thrust-weight ratio for conventional jet transports. Of course, if the lower approach lift required for RTOL aircraft is used, the thrust-weight ratios required are much smaller. As has been indicated, these curves are for externally blown flaps. The more efficient internally blown flaps require less thrust-weight ratio, as indicated in figure 12 (data from ref. 10).

Figure 12 shows the static thrust-weight ratio required as a function of approach C_L for internally and externally blown flaps. The lower thrust requirement for the internally blown flaps is apparent. However, in order to obtain a meaningful comparison of the power requirements for the internally and externally blown flaps, it is necessary to consider the characteristics of the engines used with the two flap systems. This point is illustrated in figure 13 by combining the data of figure 12 with some engine information. The curve at the right illustrates the variation with engine fan pressure ratio of the static thrust-weight ratio available with a given design cruise thrust. The engines appropriate for use with externally blown flaps have a relatively low fan pressure ratio and, hence, provide much more static thrust than the engines for internally blown flaps designed for the same cruise thrust. The dashed lines with arrows indicate that this difference in engine characteristics almost balances out the difference in flap efficiency so that the overall performance, as indicated by the approach C_L obtained with a given cruise thrust, is not greatly different for the two flap systems.

Another important factor affecting the performance of the externally blown systems is the relationship of the engine exhaust to the flap. In the case of the externally blown flap (EBF), it has been found that the amount of powered lift obtained depends on how well the flap "captures" the engine exhaust and turns it downward.

This point is illustrated in figure 14 (data from ref. 11) which shows powered-lift increment as a function of slipstream capture ratio, z/D, where z/D is defined by the sketch. The lift increment appears to vary directly as the proportion of the slipstream captured and actually continues to increase beyond a z/D of 1 where the bottom of the engine exhaust would theoretically coincide with the bottom of the flap. It has been found that this relatively simple factor z/D can satisfactorily account for changes in geometric design features such as longitudinal and vertical position of the nacelle, the incidence of the nacelle, and the relative size of the flap and engine nozzle. A paper by D. R. Hoad (ref. 12) in this conference will give more information on this subject.

In the case of the upper surface blown flap (USB), there are some other critical factors involved in the turning of the jet exhaust as indicated by figure 15 (taken from ref. 13). On this plot of engine fan pressure ratio against the ratio of jet thickness to flap turning radius, a boundary for good turning is shown. The boundary indicates that reductions in pressure ratio permit thicker jets to be used, but it has been found that even with low-fan-pressure-ratio engines, some special features are required for satisfactory turning. These special features include extreme flattening of the exhaust nozzle, a downward deflection of the nozzle, and the use of some flow control device such as boundary-layer control or vortex generators at the knee of the flap. The YC-14 AMST makes use of vortex generators along with a small nozzle deflection angle to obtain good turning. An illustration of the improvement in turning obtained with nozzle deflection angle is shown in figure 16. Note the favorable shift in the boundary with the deflected nozzle. The sketches in figure 17 (taken from ref. 13) illustrate how the deflected nozzle flattens the jet sheet to produce better turning. Since the jet sheet also spreads out, it covers a greater part of the flap span and results in improved lift performance.

It should be pointed out that the nozzle deflection angle illustrated in figures 16 and 17 may be referred to in later papers in the conference as deflector angle, kickdown angle, or nozzle roof angle. Definition of these angles may differ in detail but they all refer to a downward deflection of the exhaust over the top of the wing to flatten the jet sheet and make it turn better.

STABILITY AND CONTROL

Now let us turn from performance to stability and control considerations. A critical problem in this area for both externally blown concepts is maintaining lateral trim with an engine out. Of course, an attempt is made in the basic design of the aircraft to minimize the problem by locating the engines as far inboard on the wing as possible; but special provisions are still required to obtain lateral trim without prohibitive losses in lift. Typical engine-out rolling moments measured on EBF and USB models (refs. 13 and 14) are presented in figure 18 as a function of the engine-out lift loss. The solid line represents the rolling moments obtained by multiplying the loss in lift by the distance out to the dead engine (y/b), whereas the data points show the measured rolling moments. For both models, the fact that the measured moments are smaller than the calculated moments indicates that the center of lift induced by an engine is somewhat inboard of the engine. These measured moments, however, are still very large and require special attention on the part of the designer.

One satisfactory solution to the problem for the externally blown flap is illustrated in figure 19 (taken from ref. 14). Shown on a plot of rolling-moment coefficient against lift coefficient are the basic 4-engine $C_{L,max}$ condition, the engine-out condition with no lateral trim, and the trimmed conditions obtained with midspan differential flaps and spoilers. With both the spoilers and flaps deflected, the rolling moment is more than adequate for lateral trim; therefore, much of the spoiler effectiveness is available for maneuvering in roll.

This solution to the engine-out lateral trim problem did not work for the upper surface blown flap because of a basic difference in the flow patterns over the wing and flap, as illustrated in figure 20 (taken from ref. 13). For the externally blown flap, the flow impinges on the bottom surface of the flaps and spreads out spanwise through the flap slots so that the powered-lift effect extends well outboard of the engines. For the upper surface blown flap, the jet exhaust tends to roll up and contract, and thus pulls the lower velocity free-stream flow inward along the midspan. The midspan flap segment is therefore not very effective for providing roll trim. A much more effective roll trim for the USB configuration was found to be the use of asymmetrical boundary-layer control; that is, the use of BLC on the leading edge and aileron of the wing with the engine out but not on the other wing. Figure 21 shows some lateral trim data obtained with this method (ref. 13) which look very similar to the results obtained on the EBF model with the midspan differential flap and spoiler. This point will be covered in more detail by A. E. Phelps III and J. L. Johnson (ref. 15).

Another critical stability and control problem area for powered-lift aircraft is the design of the horizontal tail for adequate longitudinal trim and stability. Longitudinal trim is a problem because of the large nose-down pitching moments produced by powered-lift flaps at high thrust settings. The problem is illustrated in figure 22 (data from ref. 13) which shows the horizontal-tail size required to trim out these nose-down moments at various lift coefficients. Curves are shown for a 27° swept wing and an unswept wing having USB flaps. (Similar results would be expected with the EBF concept.) A tail arm $\left(l_{tail}/c\right)$ of four wing chords and a tail lift coefficient $\left(C_{L,tail}\right)$ of two have been assumed in calculating the curves. It is apparent that very large horizontal tails are required for trim at the higher lift coefficients obtained with powered lift, especially for the unswept wing. The trim requirements are smaller for the swept wing because with the engines located inboard, the powered-lift loads are acting further forward with respect to the center of gravity and therefore produce smaller nose-down moments. Even for the swept wing, however, the tail sizes required at the higher lift coefficients are much larger than the area of about 20 percent usually required for conventional transports.

This large horizontal tail must also be positioned properly on the aircraft to give satisfactory longitudinal stability, as illustrated in figure 23 (taken from ref. 14). These pitching-moment data, for a powered-lift approach condition, show the unstable tail-off curve with the large nose-down moments and two tail-on curves. With the high rearward tail location, the model is longitudinally unstable. Moving the tail forward in the high position makes the model stable, at least out to an angle of attack of 15°. Figure 24 (taken from ref. 14) shows why moving the tail forward helped the stability. The trailing vortices originating at the wing tip or outboard end of the flap move inward so that a rearward-located tail tends to move into a region of destabilizing downwash as angle of attack is increased. Locating the tail farther forward gets it farther away from the vortices and into a region of less destabilizing downwash. It is apparent from this sketch and the two preceding data figures that sizing and locating the horizontal tail for satisfactory trim and stability can be a critical design problem for powered-lift aircraft.

Another important stability and control consideration for powered-lift aircraft is the stability of the Dutch roll oscillation, as illustrated in figure 25 (taken from refs. 13 and 14). Calculated Dutch roll characteristics for USB and EBF configurations with swept and unswept wings are shown with boundaries taken from an AGARD publication outlining STOL handling criteria (ref. 16). The plot on the left shows that with the swept wing, both the USB and EBF aircraft had unsatisfactory Dutch roll stability when the lift coefficient was increased from 1.5 to 5.0. Satisfactory damping could be obtained by doubling the basic roll and yaw damping of the EBF aircraft and tripling the roll and yaw damping of the USB aircraft. In contrast, the plot on the right for the unswept wing shows that increasing the lift coefficient from 1.5 to 5.0 makes the Dutch roll stability satisfactory even with the basic roll and yaw damping. The fact that the unswept wing looks so good from the standpoint of Dutch roll, while the swept wing was shown to require a much smaller horizontal tail for longitudinal trim (fig. 22) suggests that some intermediate sweep angle (between 0° and 27°) could be a good compromise.

ACOUSTICS AND LOADS

The areas of powered-lift acoustics and loads will now be considered. A good illustration of the severity of the noise problem for powered-lift STOL aircraft is shown in figure 26 (from ref. 17) which compares the noise requirements for STOL and CTOL (conventional take-off and landing) aircraft. First, the bars at the left show the present and proposed Federal Aviation Administration (FAA) sideline noise constraints (103 to 98 EPNdB) for a sideline distance of 0.56 km (0.35 mile) or 643 m (2100 ft). If these values are converted to a sideline distance of 151 m (500 ft) they become 124 and 119 EPNdB. The bar at the right shows that the tentative STOL noise goal for this same 151-m (500-ft) sideline distance is 95 EPNdB, which means the STOL must be 24 to 29 EPNdB quieter than a conventional airplane. This stringent requirement, of course, stems from the fact that STOL aircraft are intended to operate from airports which are closer to populated areas.

Although the STOL is required to be much quieter than a CTOL, it is actually potentially noisier because it has a much higher installed thrust and operates at high thrust values during approach and landing. The solution to this problem is obviously the use of a very quiet engine; and promising research and development have been going on in this area. Unfortunately, the externally blown flap produces additional noise which compounds the problem, as illustrated in figure 27 (from ref. 18). Noise radiation patterns are shown for engine alone, for flaps retracted, and for a take-off flap deflection. There is a small increase in noise level even with flap retracted, and a very large increase when the flaps are extended down into the jet exhaust.

As indicated earlier, it was the severity of this flap impingement noise with the EBF which resulted in renewed interest in upper surface blowing. The benefit to be gained by having the exhaust flow above the wing to take advantage of the shielding effect of the wing is illustrated in figure 28 (from ref. 18) which compares noise radiation patterns and noise levels for EBF and USB flap systems with a landing flap deflection. The plot at the left shows that the USB produces more noise above the wing but produces much less noise below the wing, which is, of course, the important direction. The plot at the right shows the variation of noise with nozzle exhaust velocity for the two concepts. A substantial reduction in exhaust velocity is required with the EBF to give comparable noise levels with the USB; to obtain this lower exhaust velocity, an engine with a lower fan pressure ratio is required with the EBF. Recent developments which indicate solutions to the noise problems of both these concepts are covered in later sessions of the conference.

In the area of aerodynamic loads, one of the problems inherent in the externally blown concepts is the large static loads produced on the flaps as illustrated in figure 29 (taken from ref. 19). On this plot of the spanwise variation of flap normal force on the three flap segments, the peak loads are obtained directly behind each engine. These results were obtained on an EBF model; but similar peak values behind the engines occur for USB configurations as will be seen in a subsequent paper by B. Perry III and M. R. Mendenhall (ref. 20). Another loads problem for both of these concepts is high-intensity fluctuating loads which can induce high vibration levels and sonic fatigue. Figure 30 (taken from ref. 21) illustrates the principal sources of turbulent pressure fluctuations for both externally blown concepts. These pressure fluctuations can be generated within the engine by combustion, in the mixing region of the core or bypass exhaust jet, or in the flow impingement region by boundary layers or separated flow. The significance of the dynamic loads induced by these pressure fluctuations is illustrated in figure 31 (taken from ref. 22). The sound pressure levels of several sources of acoustic loading on aircraft are compared in bar graph form. For sound pressure levels above about 130 dB, sonic fatigue failures of light secondary structures have become a problem with the top four sources shown. It is therefore expected that blown flaps (both EBF and USB) will also be subject to sonic fatigue and that special attention must be given to this problem in the detailed design of the powered-lift system.

OTHER POWERED-LIFT CONCEPTS

Some other powered-lift concepts which have recently been receiving attention are illustrated in figure 32. First, at the top of the figure is the over-the-wing blowing arrangement which has potential application to conventional subsonic transports and supersonic transports. This concept differs from upper surface blowing in that the engine exhaust in cruising flight does not touch the upper surface of the wing. Thus, scrubbing drag is avoided and it might be possible to position the engine so that the exhaust produces a favorable rather than a detrimental interference drag. For low-speed flight, tail-pipe deflectors turn the exhaust downward against the top of the wing. Research results on this concept will be given in a subsequent paper by P. L. Coe and P. G. Fournier (ref. 23).

Another concept, illustrated at the lower left, is spanwise blowing, a technique in which a jet of air is blown out along the upper surface of the wing in a direction essentially parallel to the leading edge in order to enhance the leading-edge vortex and thereby delay vortex breakdown and wing stall to higher angles of attack. (See ref. 24.) This concept appears to be promising as a means of increasing the maneuverability of fighter aircraft. Another means of increasing fighter maneuverability, which has also been studied recently, is the use of powered-lift maneuvering flaps such as illustrated at the lower right of figure 32. Flaps of this type can provide the substantial increase in lift desired for better maneuvering capability.

CONCLUDING REMARKS

In this overview of powered-lift technology, an attempt has been made to present in a very condensed form, an objective view of both the potential and the problems of powered lift. The papers to be presented during the remainder of the conference will complete the picture and will cover some of the latest developments in the field.

REFERENCES

1. Attinello, John S.: Design and Engineering Features of Flap Blowing Installations. Boundary Layer and Flow Control, Pergamon Press, 1961, pp. 463-515.

2. Davidson, I. M.: The Jet Flap. J. Roy. Aeronaut. Soc., vol. 60, no. 541, Jan. 1956, pp. 25-50.

3. Lowry, John G.; Riebe, John M.; and Campbell, John P.: The Jet-Augmented Flap. Preprint No. 715, S.M.F. Fund Paper, Inst. Aeronaut. Sci., Jan. 1957.

4. Malavard, L.; Poisson-Quinton, Ph.; and Jousserandot, P. (T. M. Berthoff and D. C. Hazen, transl.): Theoretical and Experimental Investigations of Circulation Control. Rep. No. 358, Dept. Aero. Eng., Princeton Univ., July 1956.

5. Harris, K. D.: The Hunting H.126 Jet-Flap Research Aircraft. Assessment of Lift Augmentation Devices, AGARD-LS-43-71, Feb. 1971.

6. Quigley, Hervey C.; and Innis, Robert C.: A Flight Investigation of the STOL Characteristics of an Augmented Jet Flap STOL Research Aircraft. NASA TM X-62334, 1974.

7. Campbell, John P.; and Johnson, Joseph L., Jr.: Wind-Tunnel Investigation of an External-Flow Jet-Augmented Slotted Flap Suitable for Application to Airplanes With Pod-Mounted Jet Engines. NACA TN 3898, 1956.

8. Turner, Thomas R.; Davenport, Edwin E.; and Riebe, John M.: Low-Speed Investigation of Blowing From Nacelles Mounted Inboard and on the Upper Surface of an Aspect-Ratio-7.0 35° Swept Wing With Fuselage and Various Tail Arrangements. NASA MEMO 5-1-59L, 1959.

9. Maglieri, Domenic J.; and Hubbard, Harvey H.: Preliminary Measurements of the Noise Characteristics of Some Jet-Augmented-Flap Configurations. NASA MEMO 12-4-58L, 1959.

10. Hoad, Danny R.: Comparison of Aerodynamic Performance of Several STOL Concepts. STOL Technology, NASA SP-320, 1972, pp. 111-119.

11. Roe, Marshall H.: Air Force STOL Tactical Aircraft Investigation: Evaluation of Externally Blown Flaps. [Preprint] 730914, Soc. Automot. Eng., Oct. 1973.

12. Hoad, Danny R.: Externally Blown Flap Impingement Parameter. Powered-Lift Aerodynamics and Acoustics, NASA SP-406, 1976. (Paper no. 7 of this compilation.)

13. Johnson, Joseph L., Jr.; and Phelps, Arthur E., III: Low-Speed Aerodynamics of the Upper-Surface Blown Jet Flap. [Preprint] 740470, Soc. Automot. Eng., Apr.-May 1974.

14. Parlett, Lysle P.: Stability and Control of Externally Blown Flap Configurations. STOL Technology, NASA SP-320, 1972, pp. 55-69.

15. Phelps, Arthur E., III; Johnson, Joseph L., Jr.; and Margason, Richard J.: Summary of Low-Speed Aerodynamic Characteristics of Upper-Surface-Blown Jet-Flap Configurations. Powered-Lift Aerodynamics and Acoustics, NASA SP-406, 1976. (Paper no. 4 of this compilation.)

16. V/STOL Handling. I - Criteria and Discussion. AGARD Rep. No. 577, Dec. 1970.

17. Rulis, Raymond J.: STOL Noise Sources and Fan Noise Treatment. Aircraft Engine Noise Reduction, NASA SP-311, 1972, pp. 247-258.

18. Dorsch, Robert G.; and Reshotko, Meyer: EBF Noise Tests With Engine Under-the-Wing and Over-the-Wing Configurations. STOL Technology, NASA SP-320, 1972, pp. 455-473.

19. Greene, George C.; and Perry, Boyd, III: Aerodynamic Loads Measurements on Externally Blown Flap STOL Models. STOL Technology, NASA SP-320, 1972, pp. 121-130.

20. Perry, Boyd, III; and Mendenhall, Michael R.: Measured and Calculated Steady Aerodynamic Loads on a Large-Scale Upper-Surface-Blown Model. Powered-Lift Aerodynamics and Acoustics, NASA SP-406, 1976. (Paper no. 26 of this compilation.)

21. Mixson, John S.; Shoenster, James A.; and Willis, Conrad M.: Fluctuating Pressures on Aircraft Wing and Flap Surfaces Associated With Powered-Lift Systems. AIAA Paper 75-472, Mar. 1975.

22. Lansing, Donald L.; Mixson, John S.; Brown, Thomas J.; and Drischler, Joseph A.: Externally Blown Flap Dynamic Loads. STOL Technology, NASA SP-320, 1972, pp. 131-142.

23. Coe, Paul L., Jr.; and Fournier, Paul G.: Application of Powered-Lift Concepts for Improved Cruise Efficiency of Long-Range Aircraft. Powered-Lift Aerodynamics and Acoustics, NASA SP-406, 1976. (Paper no. 5 of this compilation.)

24. Campbell, James F.: Augmentation of Vortex Lift by Spanwise Blowing. AIAA Paper No. 75-993, Aug. 1975.

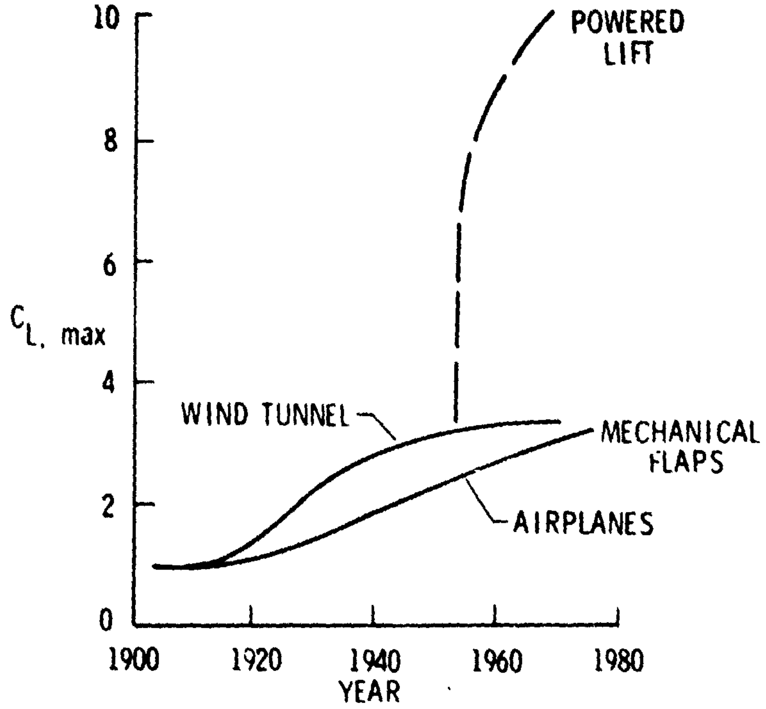

Figure 1.- Maximum lift history.

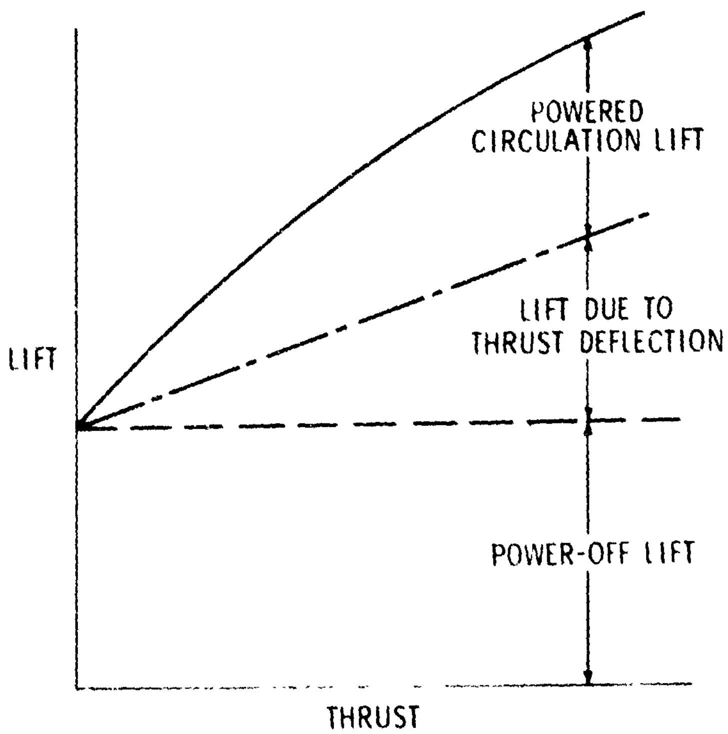

Figure 2.- Components of powered lift.

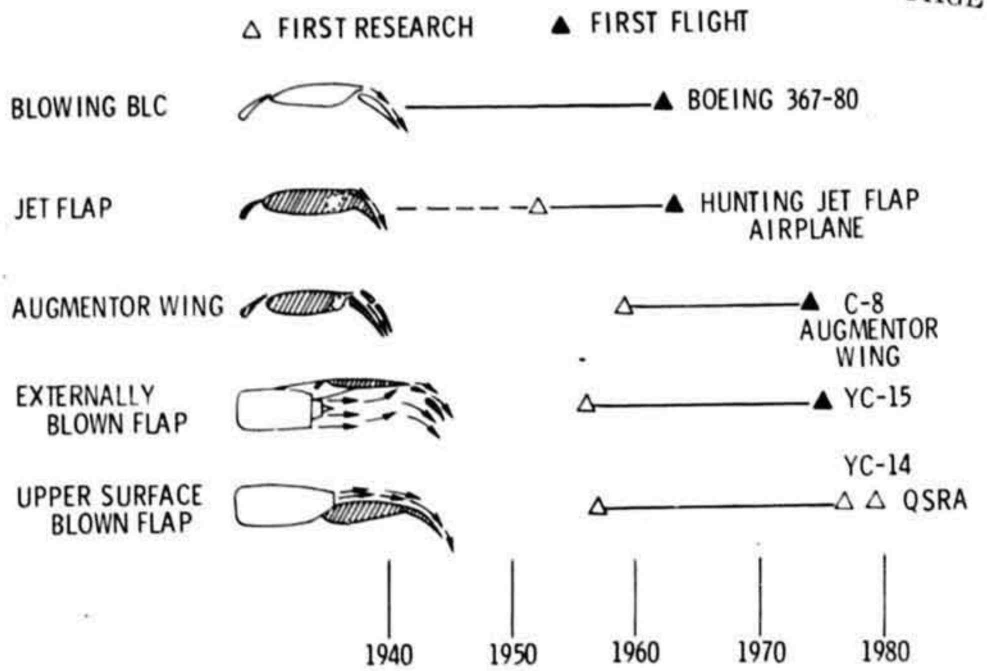

Figure 3.- Powered-lift chronology.

Figure 4.- Boeing 367-80 BLC airplane.

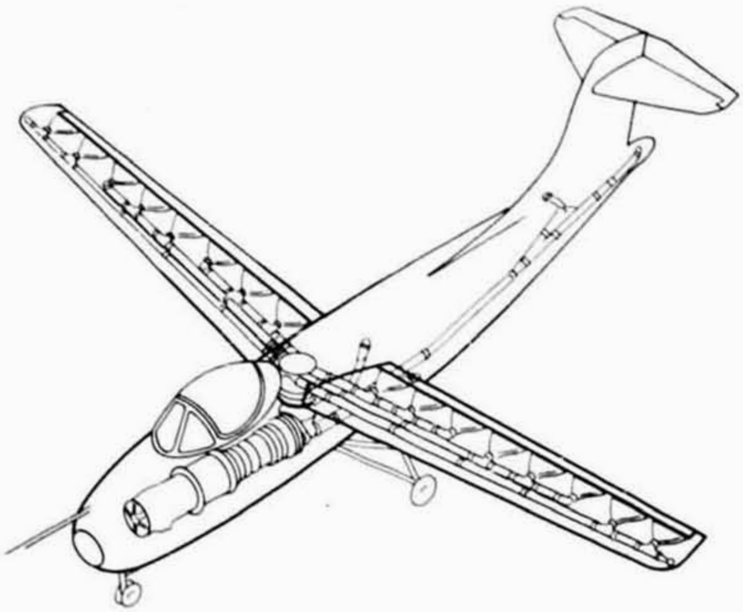

Figure 5.- Hunting jet-flap airplane.

Figure 6.- C-8 augmentor wing airplane.

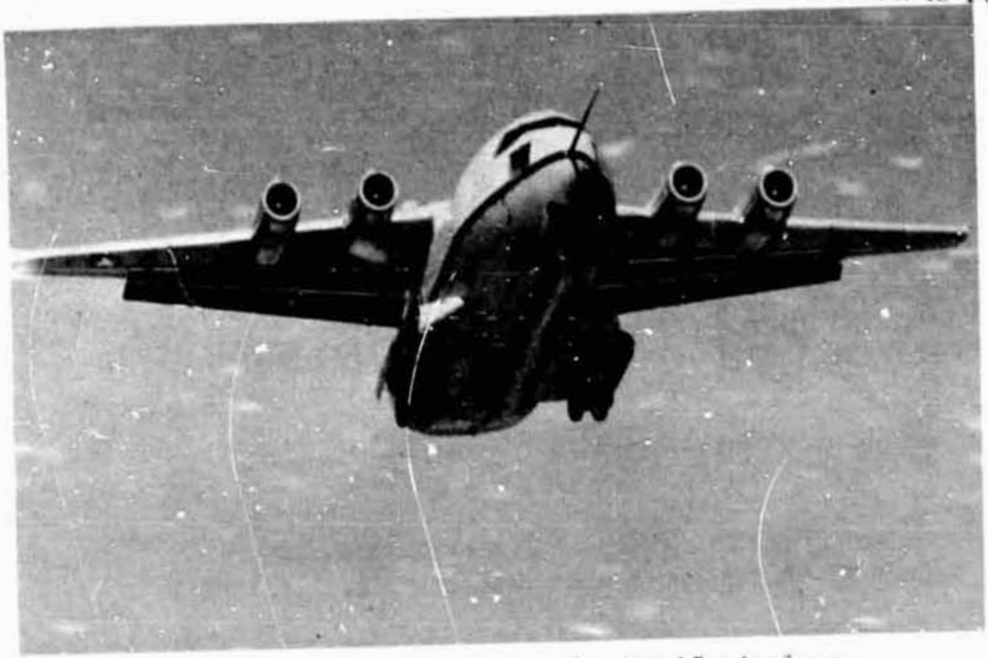

Figure 7.- McDonnell-Douglas YC-15 airplane.

Figure 8.- Boeing YC-14 airplane.

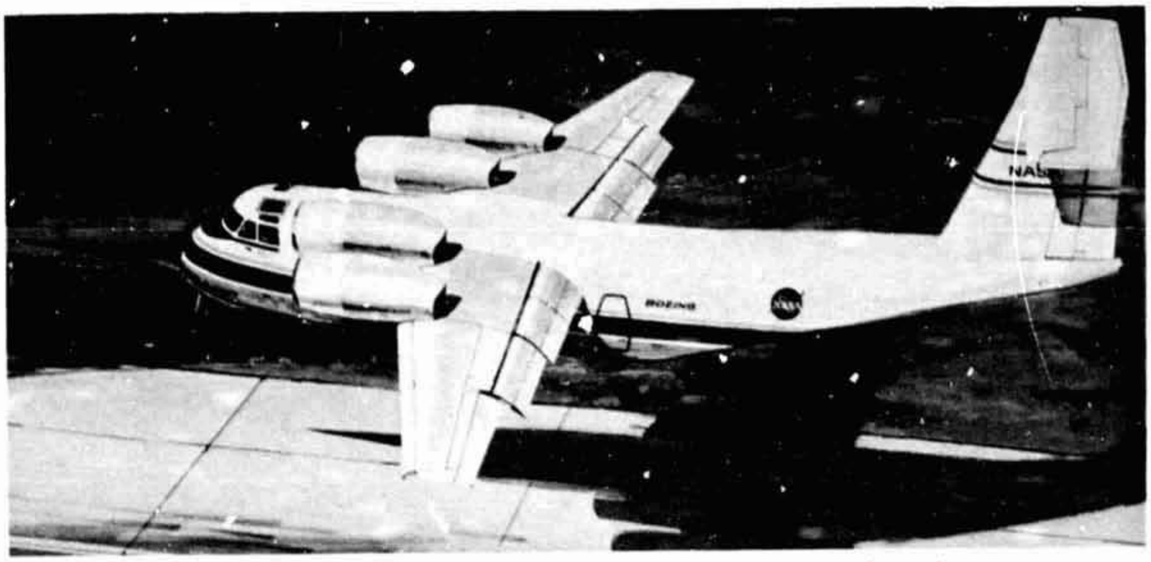

Figure 9.- Quiet short-haul research aircraft (QSRA).

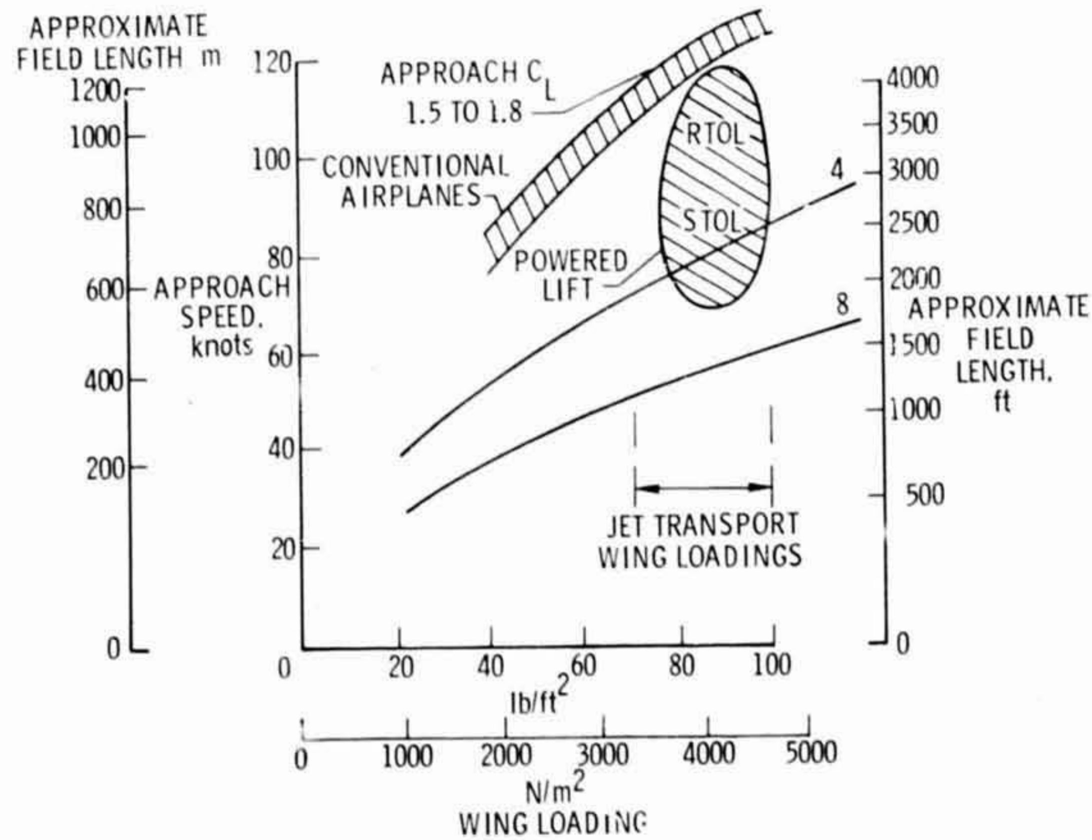

Figure 10.- Field length considerations.

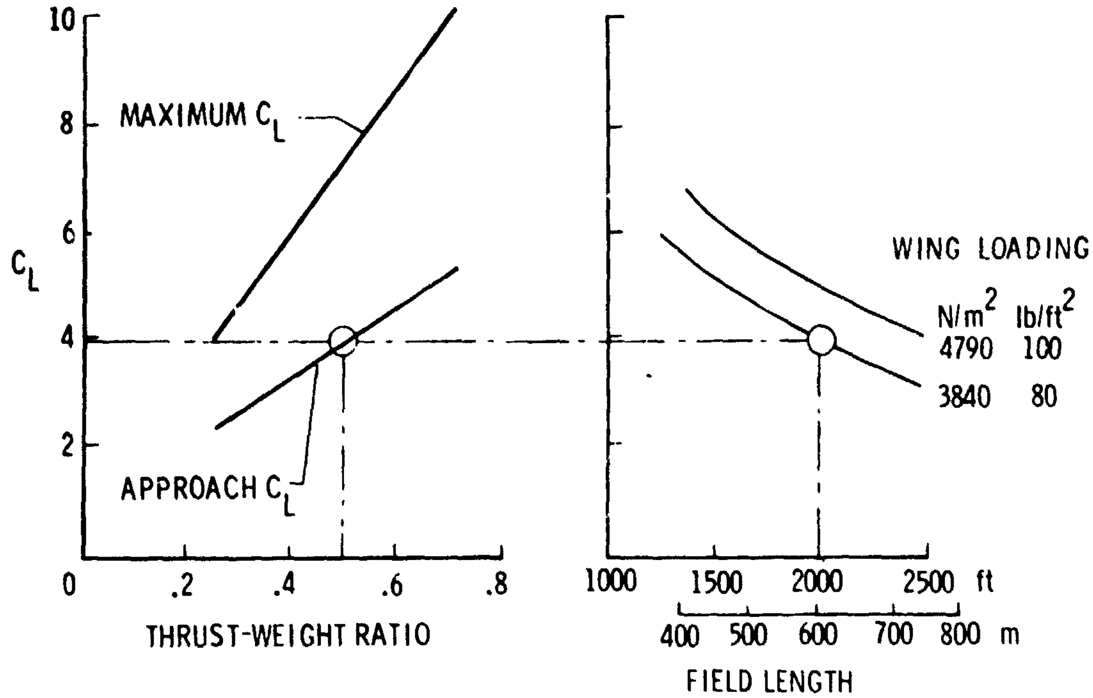

Figure 11.- Landing performance of powered-lift aircraft.

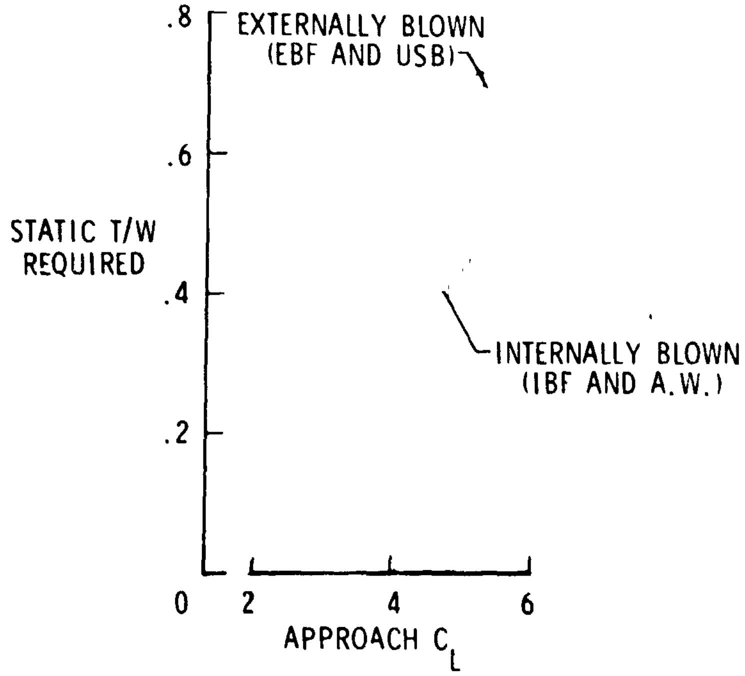

Figure 12.- Performance of externally and internally blown flaps.

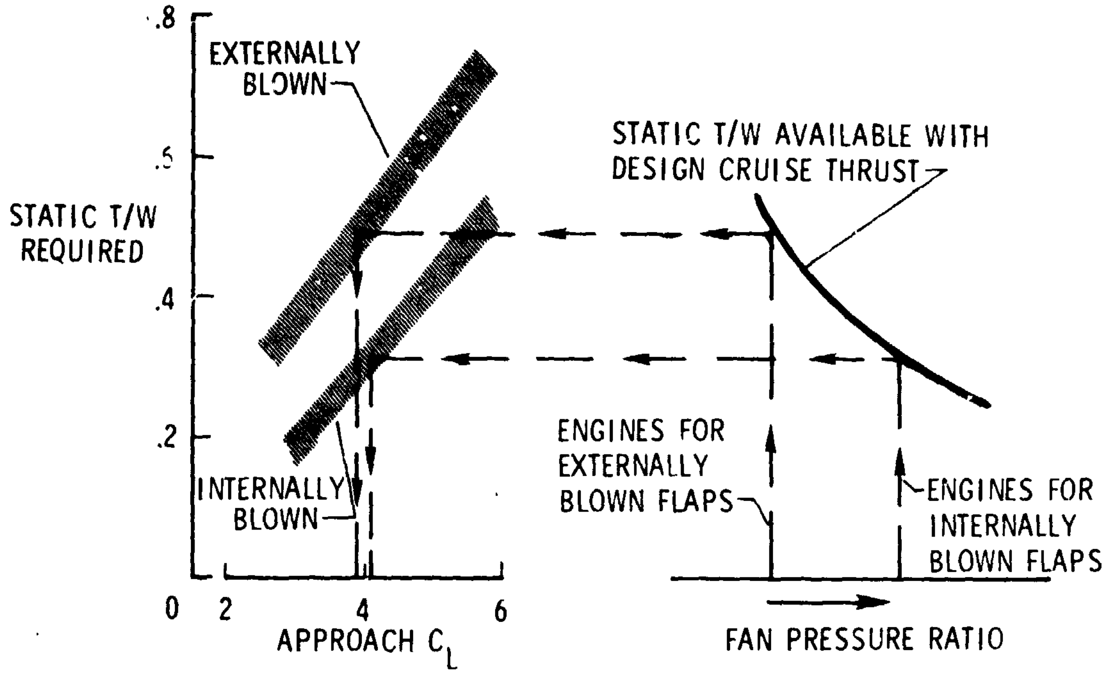

Figure 13.- Performance comparison including engine characteristics. Externally and internally blown flap systems.

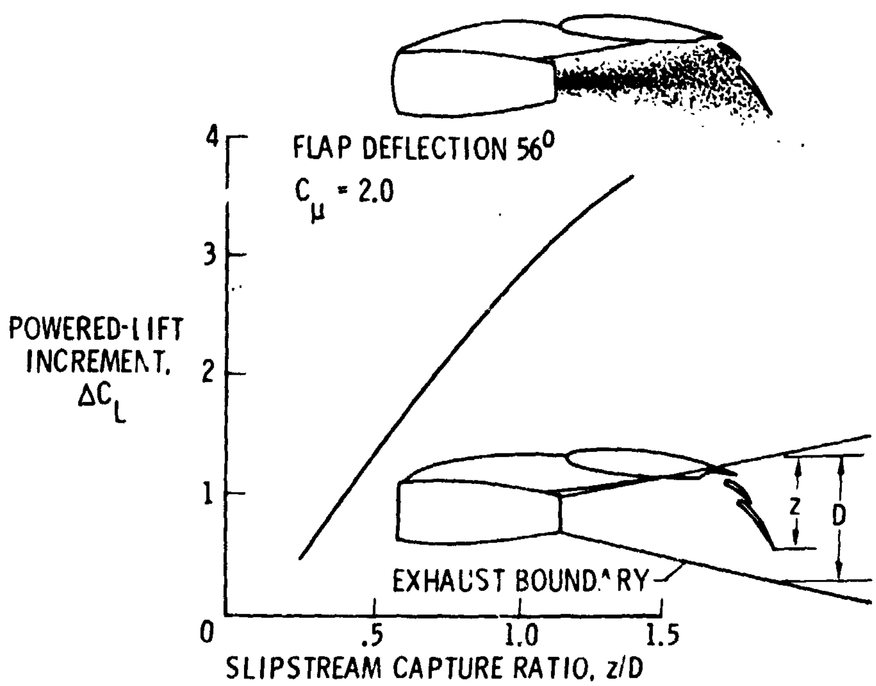

Figure 14.- Slipstream capture. Externally blown flap.

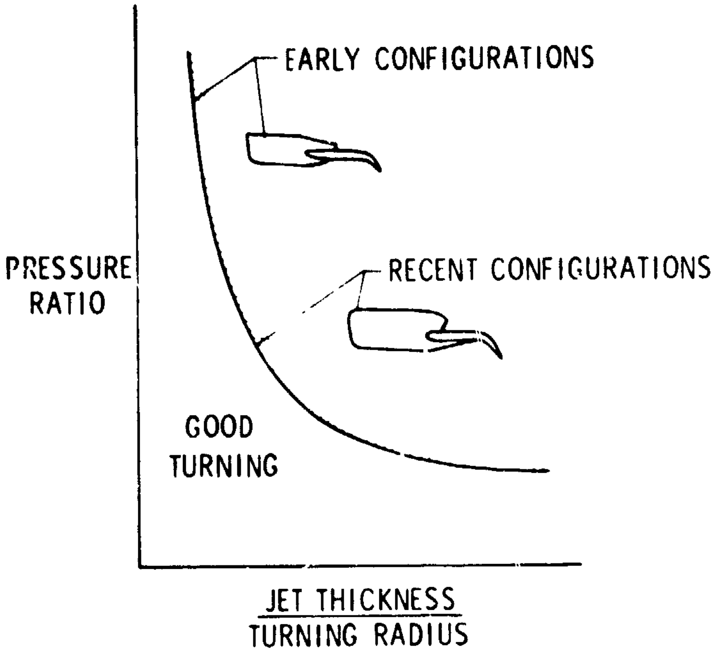

Figure 15.- Static turning.

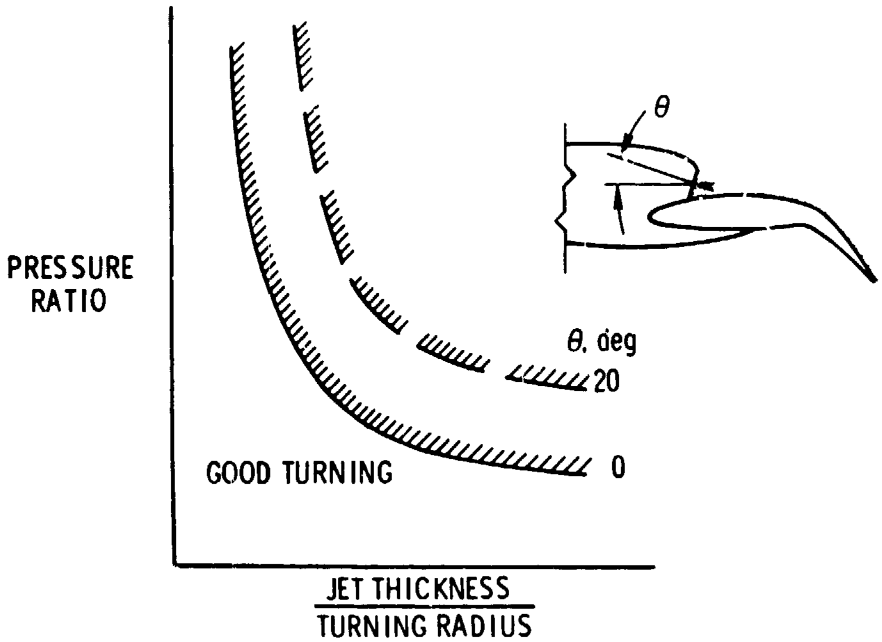

Figure 16.- Effect of nozzle deflection angle.

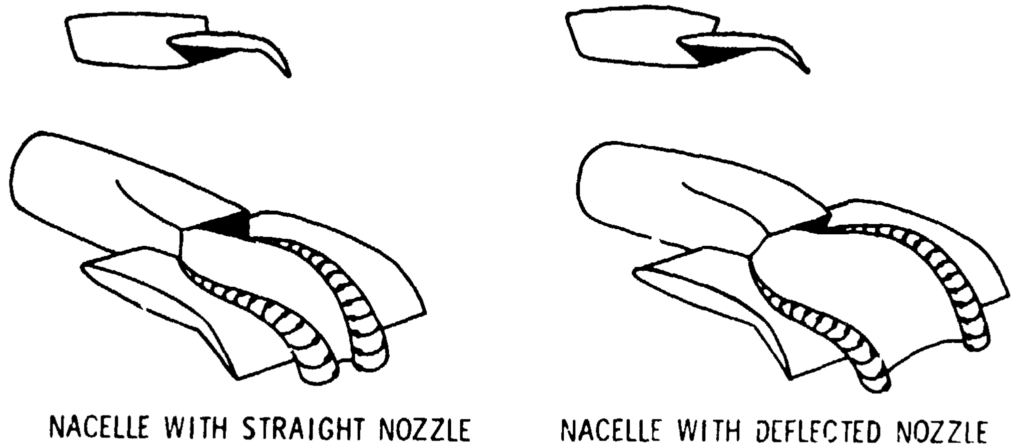

Figure 17.- Flow characteristics behind nacelles.

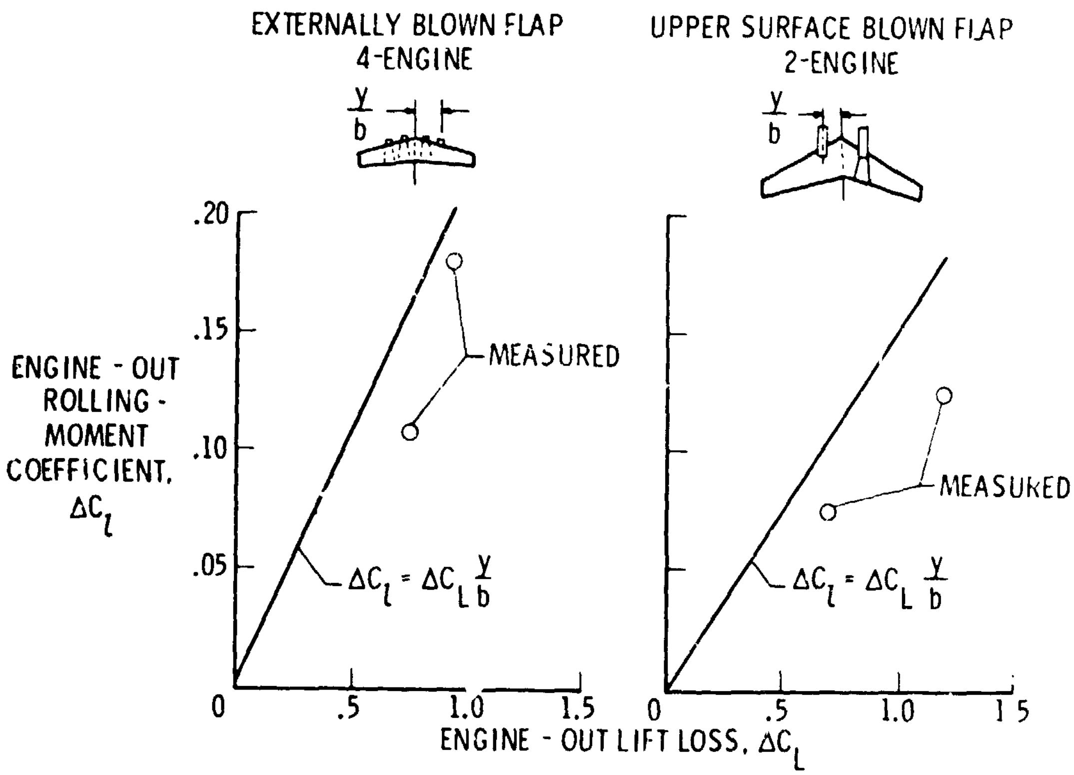

Figure 18.- Engine-out rolling moments.

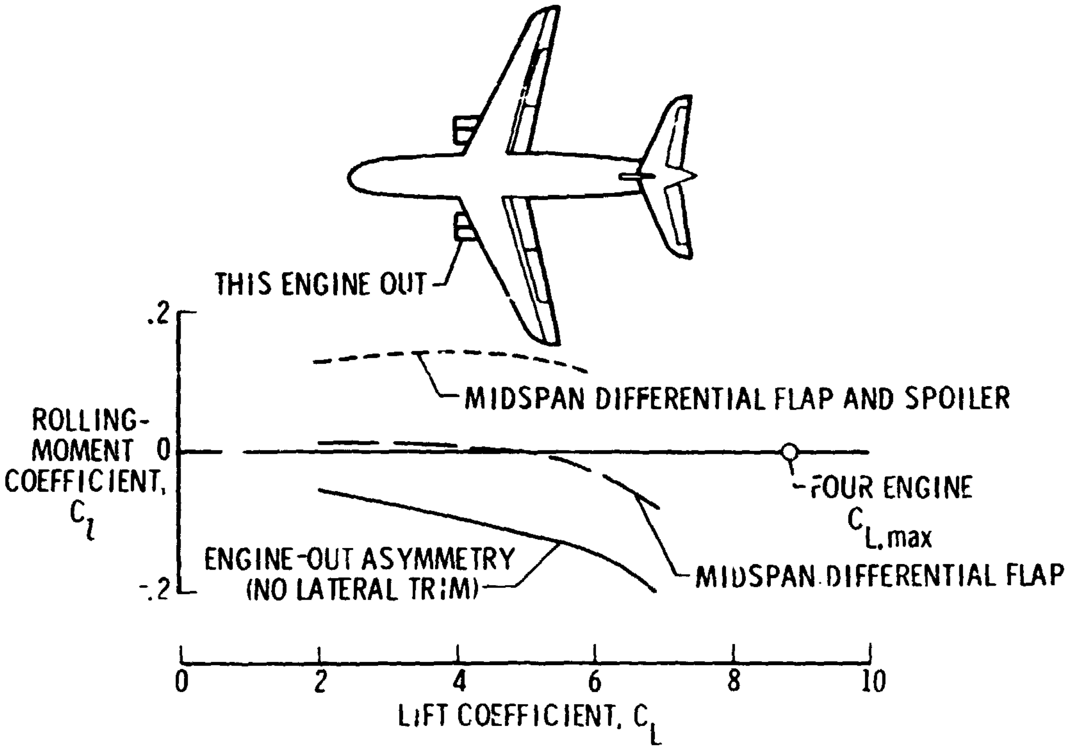

Figure 19.- Engine-out lateral trim. Externally blown flap.

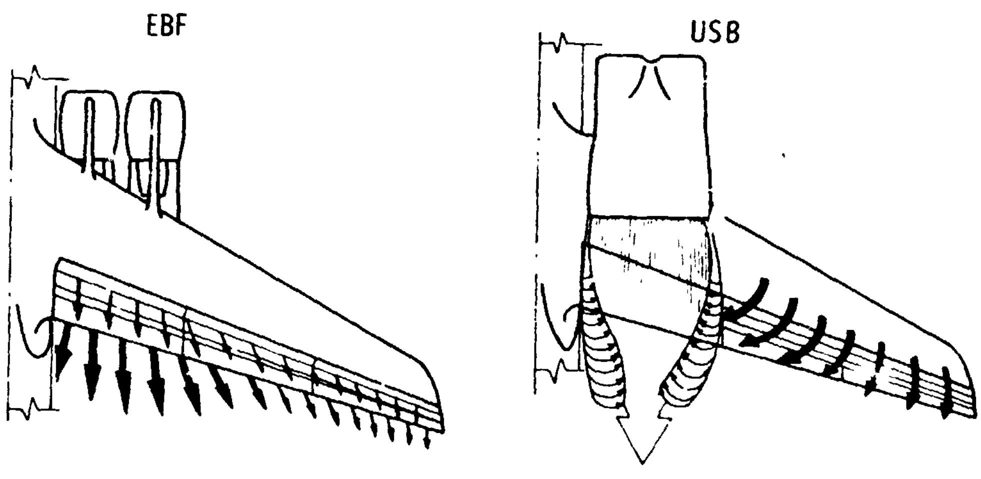

Figure 20.- Comparison of flow patterns for EBF and USB models.

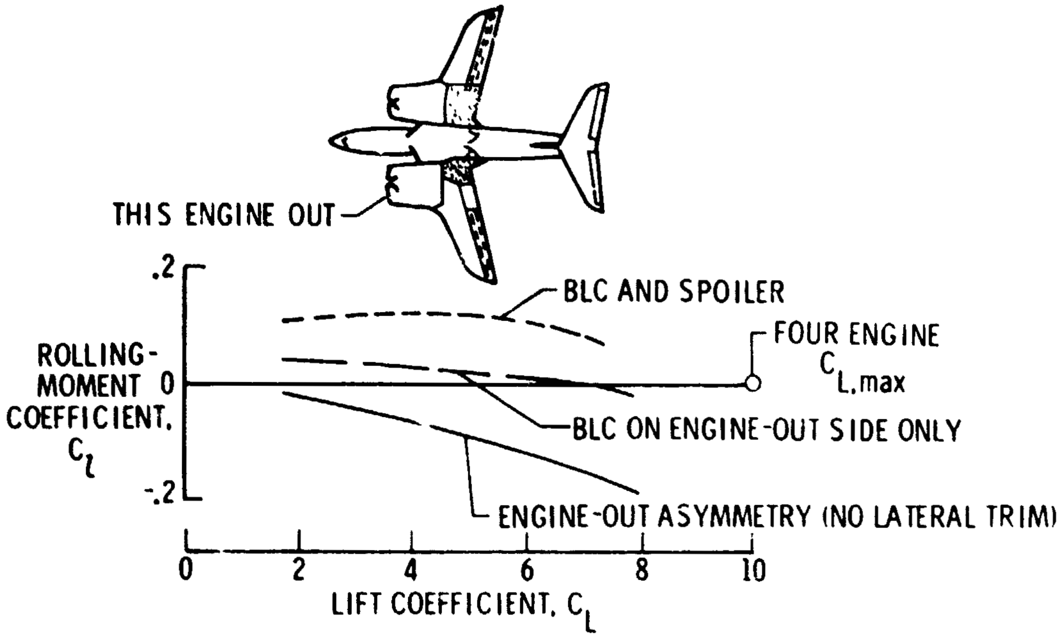

Figure 21.- Engine-out lateral trim.
Upper surface blown flap.

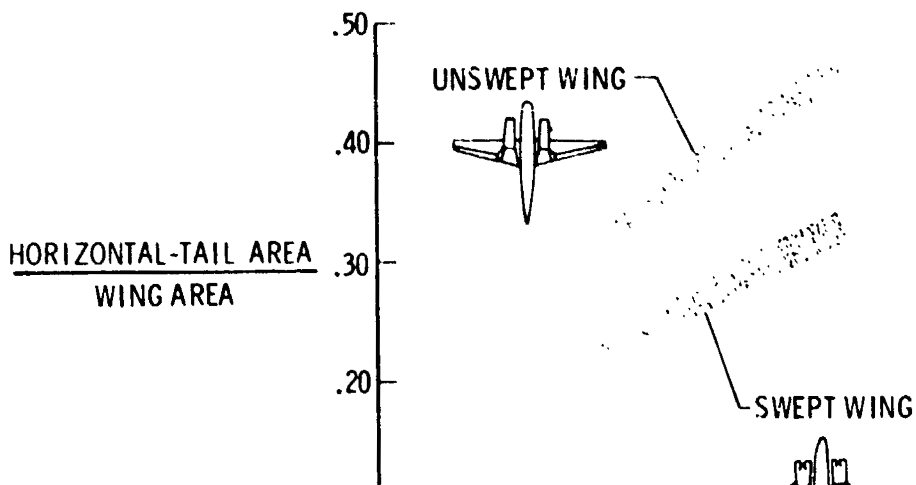

Figure 22.- Horizontal-tail size required for trim.
USB flap; $l_{tail}/c = 4$; $C_{L,tail} = 2$.

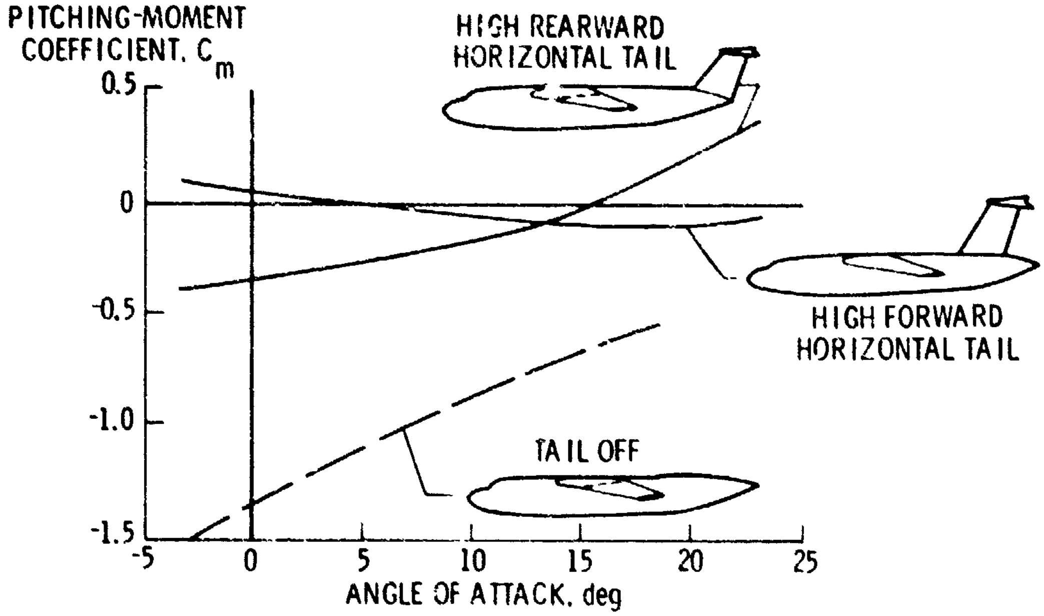

Figure 23.- Longitudinal stability.

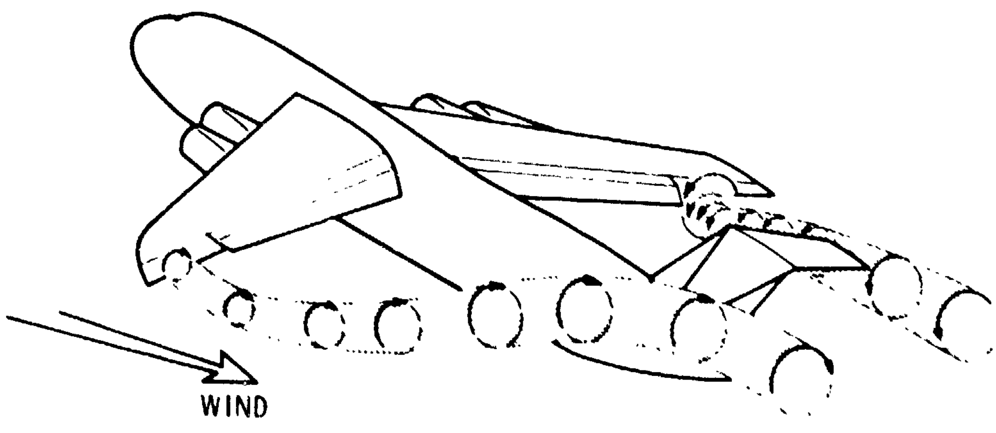

Figure 24.- Wing vortex flow.

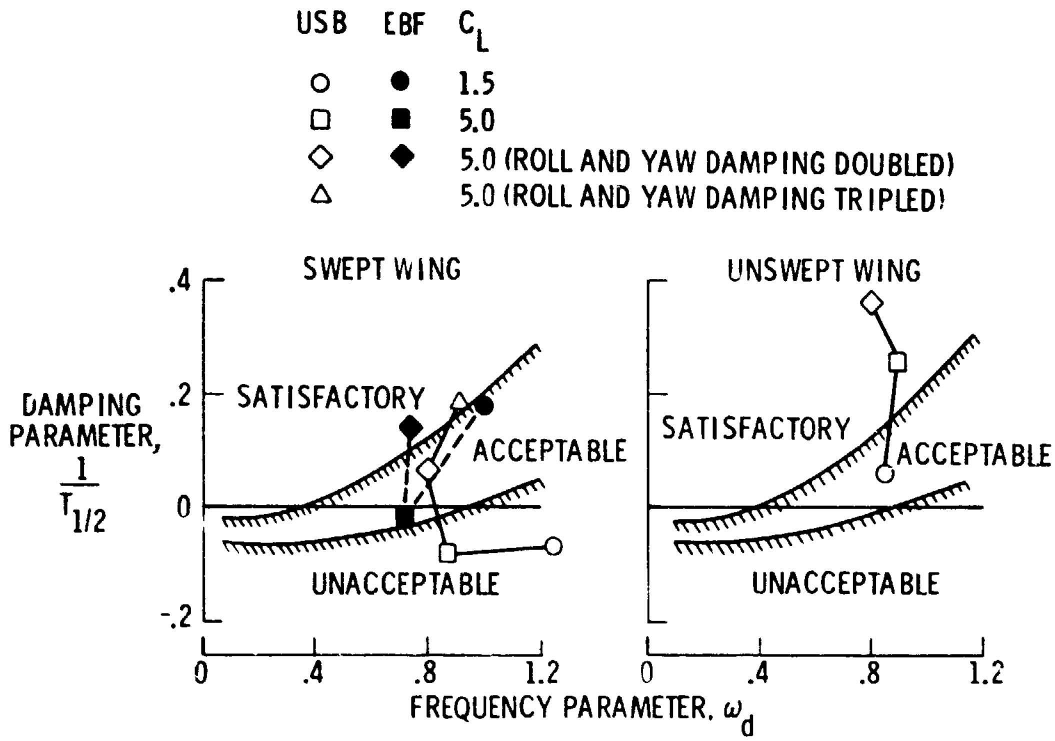

Figure 25.- Dutch roll characteristics.

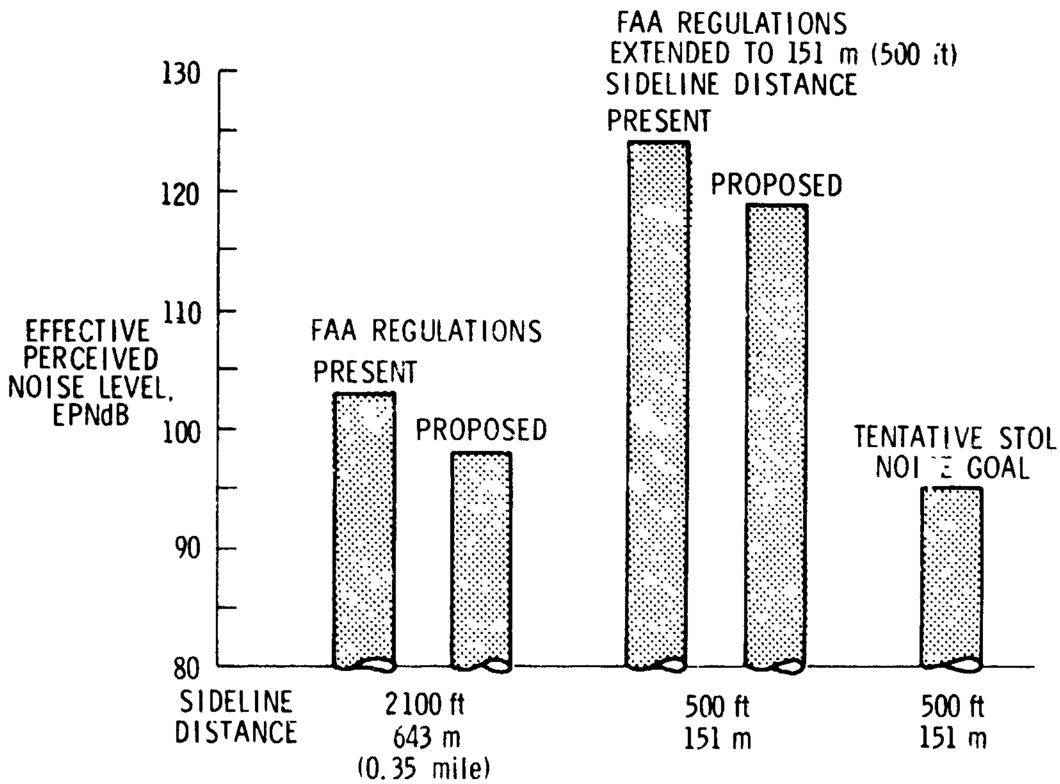

Figure 26.- CTOL and STOL noise requirements. 672 000 N (150 000 lb) aircraft.

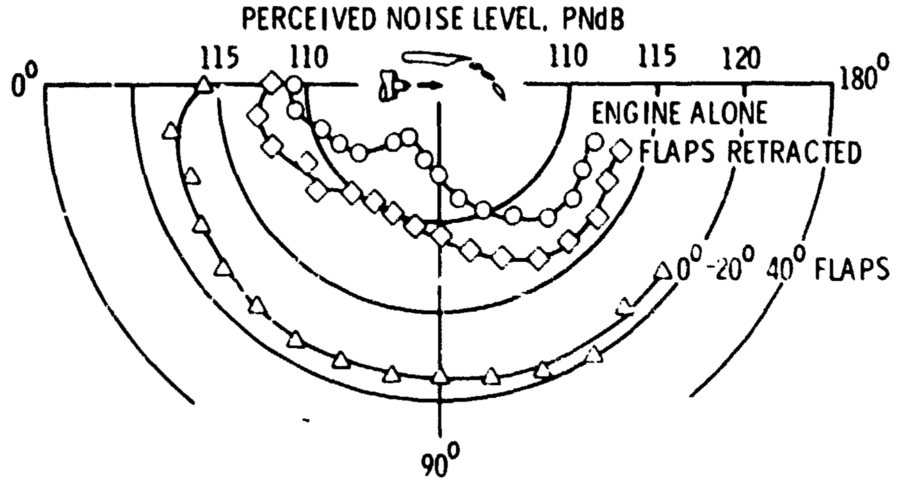

Figure 27.- EBF noise radiation patterns.
30.4 m (100 ft) from noise source.

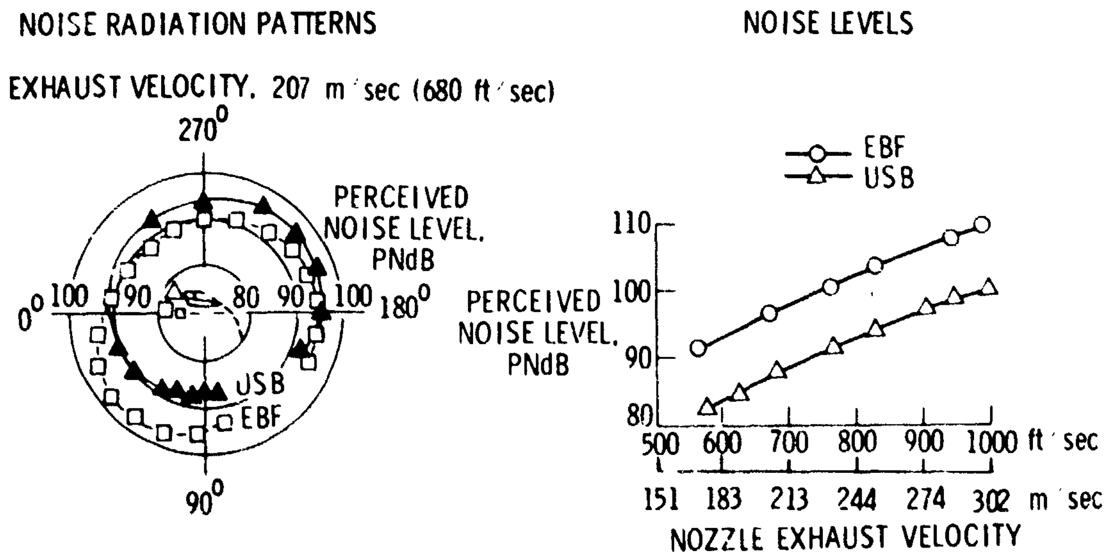

Figure 28.- Comparison of EBF and USB noise.
151 m (500 ft) from noise source; $30^0/60^0$ flaps.

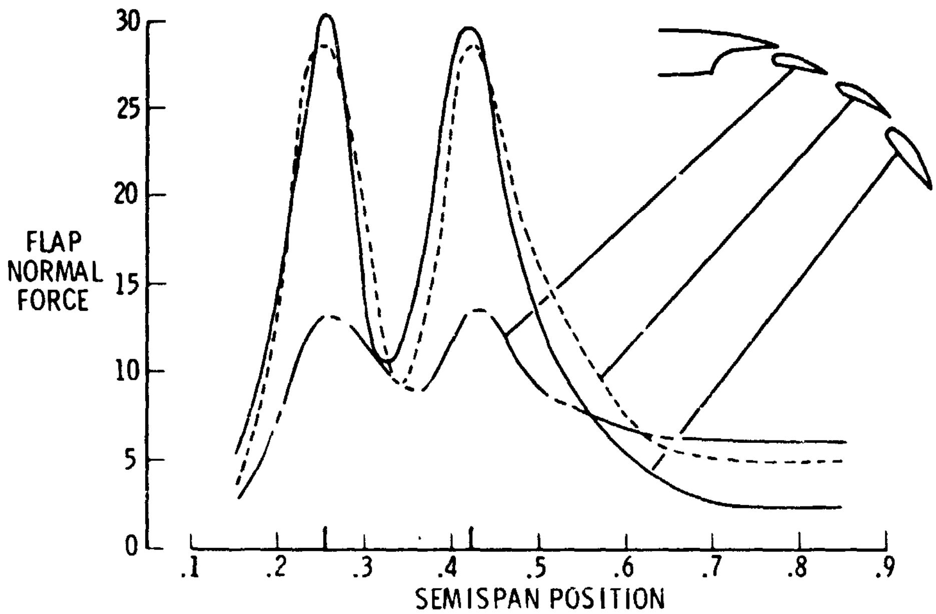

Figure 29.- Spanwise variation of flap normal force. 4-engine EBF, landing flaps ($15^{o}/35^{o}/55^{o}$); $\alpha = 16^{o}$; $C_{\mu} = 4.0$.

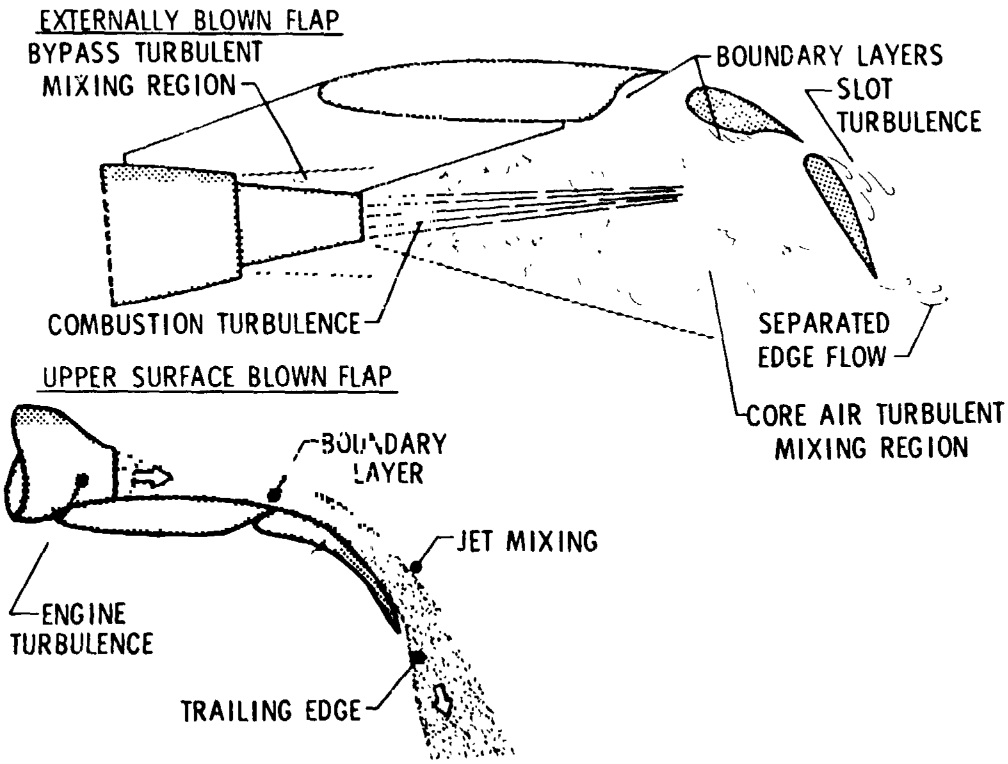

Figure 30.- Sources of fluctuating pressure on blown flaps.

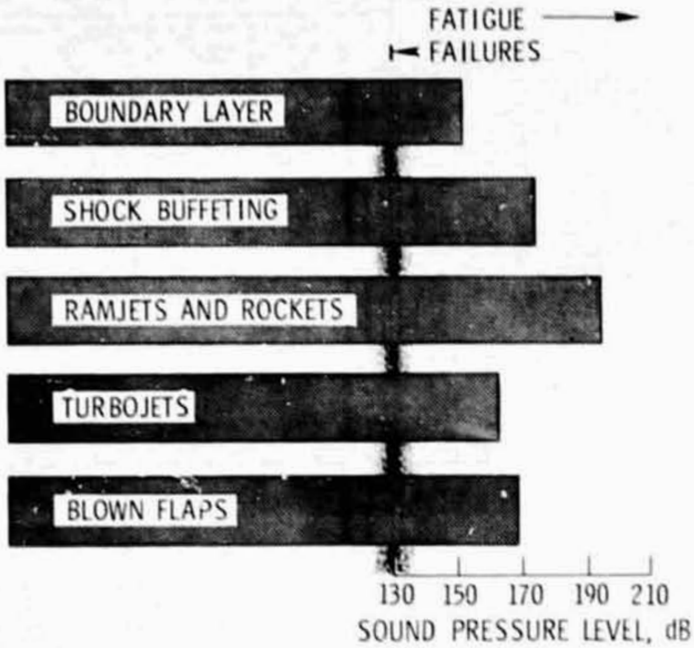

Figure 31.- Sound pressure levels of acoustic loading on aircraft structures.

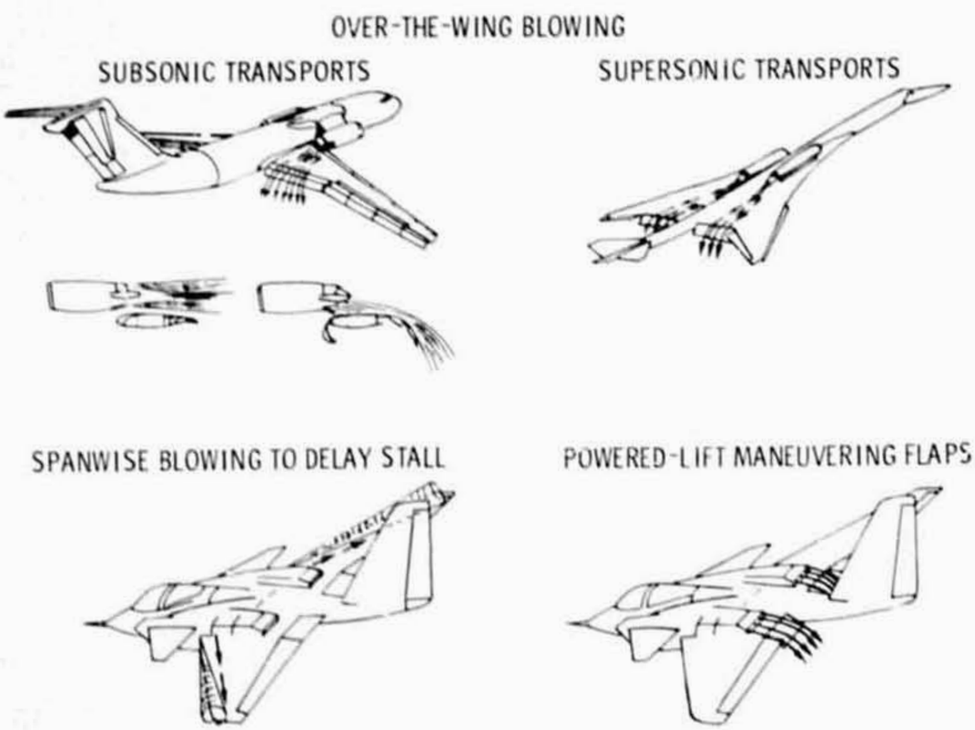

Figure 32.- Other powered-lift concepts.